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# **Economics of Carbon Capture and Storage**

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## **Abstract**

Human-engineered capture of CO<sub>2</sub> emissions at the point source and subsequent long-term storage of this CO<sub>2</sub> underground represent a potential mitigation strategy for global warming. The so-called carbon capture and storage (CCS) projects are technically feasible but have not been well established from an economic efficiency perspective. This chapter uses economic theory to describe the costs, benefits, and economically efficient level of CCS provision. Achieving the economically efficient level of CCS provision requires consideration of both the private and public costs and benefits of CCS and will also likely require some degree of government intervention in the form of economic incentives and/or direct regulation.

**Keywords:** CO<sub>2</sub>, emissions, point source, capture, storage, economics, costs, benefits

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## **1. Introduction**

Since the late twentieth century, a newly developed technology has become one of the tools that can help mitigate the negative impacts on climate change from rising levels of greenhouse gases, especially CO<sub>2</sub>. This technology is commonly known as the carbon capture and storage (CCS). CCS technology involves “capturing” CO<sub>2</sub> emissions, say from a coal-fired power plant, and then depositing the captured CO<sub>2</sub> gas in a storage site, such as an underground geological formation, where it will not enter the atmosphere. CCS projects are currently being tested and implemented throughout the world. However, economic feasibility of human-engineered CCS is not well established [1–4]. The purpose of this chapter is to discuss the economic benefits and costs of CCS projects from both private and public perspectives in order to shed light and provide insight on the potential for CCS technology to

provide a viable mitigation strategy for helping to meet twenty-first century global CO<sub>2</sub> emission reduction goals, such as set forth in the 2015 United Nations Climate Change Conference in Paris, France.

## 2. Carbon and oxygen cycles<sup>1</sup>

Carbon (C) is the basic building block for plant, animal and human life—all are “carbon-based” organisms. Plants, animals, and humans also depend on oxygen (O<sub>2</sub>) for survival. The cycling of carbon and oxygen in ecosystems is ultimately powered by solar energy. In photosynthesis, plants combine carbon dioxide (CO<sub>2</sub>), water (H<sub>2</sub>O), and solar energy to produce sugars, oxygen, and energy. In cellular respiration, animals and humans combine sugars and oxygen to produce carbon dioxide, water, and energy. Carbon-oxygen-hydrogen compounds (e.g., sugars) pass through the food chain or web in ecosystems via herbivores, carnivores, and omnivores. In the food chain, some of the carbon and oxygen stored in organic compounds are returned to the environment in the form of CO<sub>2</sub> and H<sub>2</sub>O via cellular respiration. When a large organism such as a plant or an animal dies and is decomposed by microorganisms, more of the CO<sub>2</sub> and H<sub>2</sub>O stored within the plant or animal is returned to the environment where it can be taken up again by plants to produce more carbon-oxygen-hydrogen compounds which can then be taken up again by animals and humans.

Not all carbon and oxygen are recycled in the relatively short-term cycle described above. Some carbon and oxygen from decomposing plants and animals are converted by relatively long-term geologic processes into rocks (e.g., carbonate rock formations such as limestone) and minerals (e.g., coal, oil, and natural gas) stored in the earth’s crust. When coal, oil, and natural gas enter economic systems, they are termed fossil fuels. The “fossil” part of this term derives from the fact that they come from fossilized remains of plants and animals. The “fuel” part is derived from the fact that coal, oil and natural gas, and their processed derivatives (e.g., gasoline) are burned as fuel in engines and other machinery found throughout our economic system (e.g., planes, trains, automobiles, electricity power plants, and home furnaces). When fossil fuels are burned, CO<sub>2</sub> (and other emission gases—CH<sub>4</sub>, N<sub>2</sub>O) stored in these minerals is released back into the environment. The release of CO<sub>2</sub> from burning fossil fuels is the focus of recent concern and debate over global climate change.

As indicated in the discussion above, human activities affect global climate change through impacts on the carbon and oxygen cycle. Burning of fossil fuels is a major contributor to releasing more CO<sub>2</sub> into the atmosphere, primarily from terrestrial sources of stored carbon (e.g., coal deposits, oil deposits, and trees). Human activities can also help to remove CO<sub>2</sub> from the atmosphere, with one of the primary means being increasing the storage of carbon in terrestrial plants. For example, taking actions to protect “green space” including farmland from development (and managing forests in a sustainable manner following an optimal harvest and replanting schedule) helps to remove CO<sub>2</sub> in the atmosphere through carbon sequestration in plants via photosynthesis. Farms, forests, and other green space

<sup>1</sup>This section appears also in Ref. ([5], p. 16–18).

areas thus act as “carbon sinks” helping to counteract the greenhouse effect. Another means for storing carbon is through human-engineered carbon capture and storage projects.

### 3. CCS costs

#### 3.1. Components of total fixed costs and total variable costs

CCS projects are not cheap. For example, in the United States, NRG Energy and JX Nippon Oil and Gas Exploration, Inc., are investing around \$1 billion USD on the Petra Nova CCS project. This project when completed in late 2016 is projected to capture and store about 1.4 million tons of carbon per year from one of NRG’s existing coal-fired power plants in the State of Texas, USA [6, 7]. In this section, we discuss the concepts and components of CCS costs.

First, we need to realize that CCS projects are actually two interconnected projects in one. The first project is “carbon capture” and the second project is “carbon storage.” Each of these projects has various options with different costs. As indicated in the previous section, ecosystems via the carbon and oxygen cycle will naturally capture carbon dioxide from the air (e.g., through photosynthesis) and then store the captured carbon in plants, the soil, and rocks and minerals. While CCS through natural ecosystem processes and functions is a viable mitigation strategy in response to CO<sub>2</sub>-induced global climate change concerns (e.g., planting trees), the focus of this chapter is on human-engineered CCS.

In the case of carbon capture, human-engineered means of capturing carbon focus on “end-of-pipe technologies” that remove CO<sub>2</sub> from industrial emissions, particularly fossil fuel-fired (e.g., coal) electricity power plants. The “best available technology” (BAT) in the current time period (2016) is chemical absorption of CO<sub>2</sub> from emissions at the point source (e.g. power plant smokestack). Once the CO<sub>2</sub> has been removed from emissions, say from a coal-fired power plant, the CO<sub>2</sub> can then be converted by pressurization to a liquid for transportation and storage [1, 2, 8].

Thus, one component of the costs of human-engineered carbon capture is the costs of the equipment (e.g., “scrubbers”) and absorption chemicals used to remove CO<sub>2</sub> from emissions [4, 9]. From a neoclassical microeconomics theory perspective, the “scrubber” equipment costs are “fixed costs” and the absorption chemicals are “variable costs.” Fixed costs are so-called because they are a sunk cost which does not vary with the level of production. For example, once purchased and installed, a coal-fired power plant owner must incur the costs of scrubber equipment whether they are producing electricity or not (e.g., they still have to pay off the equipment as a capital cost).

Variable costs are so-called because they vary with the level of production. For example, as more (less) electricity is produced from a coal-fired power plant, more (less) emissions are generated, and more (less) absorption chemicals must be purchased. The fixed costs of human-engineered carbon capture can be quantified by multiplying the units of equipment purchased by the market price of equipment per unit (plus loan fees and interest if the equipment is

financed). The variable costs can be quantified by multiplying, say the units of absorption chemicals purchased by the market price of chemicals per unit.

In addition to the direct, out-of-pocket fixed and variable costs of carbon capture discussed above, there are also opportunity costs of human-engineered carbon capture. For example, from an energy use perspective, human-engineered carbon capture at an electricity power plant comes with an energy use cost in the form of electricity generation that must be given up in support of carbon capture at the plant. This so-called energy penalty can be quantified by multiplying the amount of electricity lost in order to support carbon capture times the market price of electricity [2, 9–11].

After carbon is captured at a point source such as a coal-fired electricity power plant, it must be transported to and stored at a long-term storage site. At the time this chapter is being written, the most practical long-term storage sites appear to be various forms of natural underground geologic cavities (NUGCs). One option under this category is NUGC which once held crude oil and/or natural gas deposits but has been depleted through mining (e.g., oil and gas wells). Oil and gas companies already inject  $\text{CO}_2$  into operational oil and gas wells in order to squeeze more oil and gas out of the resource deposit. Thus, the technology for injecting  $\text{CO}_2$  captured from point source emissions into NUGCs where oil and gas deposits have been depleted through mining is well proven [9, 12, 13].

Because natural deposits of oil and gas have been stored by the carbon and oxygen cycle (see above) in NUGCs for thousands and millions of years, NUGCs have displayed the ability to store new  $\text{CO}_2$  injected into these formations for long periods of time with minimal leakage of  $\text{CO}_2$  back into the atmosphere. In addition to NUGCs where oil and gas deposits have been depleted, geologists and engineers can locate new NUGCs capable of storing large quantities of  $\text{CO}_2$  with minimal leakage for long time periods [9, 13].<sup>2</sup>

In order for carbon captured at the point source to be stored at long-term storage site, it must be transported from the point source to the storage site. The process for transport is generally to convert  $\text{CO}_2$  captured at the point source to a liquid through pressurization, and then move this liquid to the storage facility by truck, train, or pipeline. Assuming that NUGCs are used for long-term storage, the costs of carbon storage will mostly be the fixed and variable costs of converting  $\text{CO}_2$  to a liquid, transporting it to the storage site, and then injecting it into the NUGCs [9, 13]. After injecting the  $\text{CO}_2$  into an NUGC, the ongoing costs of storage should be minimal (e.g., limited to costs of monitoring for leakages).

The fixed costs of carbon storage (including transportation) include the costs of pressurized transport trucks and train cars, and the costs of installing a pipeline. Fixed costs also include the costs of any equipment needed to remove captured  $\text{CO}_2$  from a truck, train car, or pipeline and inject it into NUGCs. These fixed costs can be quantified by multiplying the units of equipment (e.g., transport truck or rail car) purchased by its market price per unit. The variable costs of carbon storage include payments to labor (e.g., workers who operate and main-

<sup>2</sup>As discussed in Section 2, natural chemical cycles convert carbon to hard rock and mineral deposits which further enhances long-term storage with minimal leakage.

tain trucks, trains, pipelines, and injection equipment), purchase of replacement parts, and the costs of fuel and power needed to operate and maintain trucks, trains, pipelines, and injection equipment. These variable costs can be quantified by multiplying the units employed (e.g., number of workers) or purchased (e.g., number of replacement parts) by the market wage rate for labor or the market price for replacements parts [8, 9, 13].

We can now define the total costs of carbon capture and storage ( $TC_{ccs}$ ) as

$$TC_{ccs} = (TFC_{ccs}^c + TVC_{ccs}^c) + (TFC_{ccs}^T + TVC_{ccs}^T) + (TFC_{ccs}^s + TVC_{ccs}^s) \quad (1)$$

where

$TFC_{ccs}^c$  = is the total fixed costs of carbon capture at the point source;

$TVC_{ccs}^c$  = the total variable costs of carbon capture at the point source;

$TFC_{ccs}^T$  the total fixed costs of captured carbon transportation to storage site;

$TVC_{ccs}^T$  the total variable costs of captured carbon transportation to storage site;

$TFC_{ccs}^s$  the total variable costs of carbon storage at storage site;

$TVC_{ccs}^s$  is the total variable costs of carbon storage at storage site.

With respect to economic efficiency, it is imperative we measure the marginal costs of human-engineered CCS. The short-run marginal costs ( $MC_{ccs}$ ) of human-engineered CCS are defined as

$$MC_{ccs} = \frac{\partial TC_{ccs}}{\partial Q_{CO_2}} \quad (2)$$

where  $Q_{CO_2}$  = is the quantity of  $CO_2$  captured and stored.

### 3.2. Measures of total marginal fixed costs and marginal variable costs

In practice, there are two common measures used in the cost-benefit analysis to make per-unit CSS costs and benefits comparably equivalent for any given potential level of optimal quantities of carbon dioxide ( $CO_2$ ) being captured and stored. These units are measured through time and space either in millions of tons of carbon (MtC) or of  $CO_2$  (Mt $CO_2$ ) avoided per year, that is, MtC/year or Mt $CO_2$ /year.

As described above in the definition of the total costs of carbon capture and storage ( $TC_{ccs}$ ),  $TC_{ccs}$  consists of total fixed costs and total variable costs of carbon capture at the point of source, captured carbon transportation to storage, and carbon storage at the storage site. With respect to economic efficiency, the marginal cost ( $MC_{ccs}$ ) is the imperative measure of the costs of human-engineered carbon capture and storage technology. In this chapter, marginal costs of employed CCS technology ( $MC_{ccs}$ ), as well as marginal benefits received from employed CCS technology ( $MB_{ccs}$ ), are quantified as US dollar per ton carbon (\$/tC) or US



dollar per ton carbon dioxide ( $\$/\text{tCO}_2$ ),<sup>3</sup> where one ton of carbon equals 3.67 tons of carbon dioxide.<sup>4</sup>

According to recent literature, an estimated avoided total cost of CCS per unit ( $\text{MC}_{\text{CCS}}$ ) is between US  $\$225/\text{tC}$  and  $\$315/\text{tC}$  (or US  $\$61/\text{CO}_2$  and  $\$86/\text{tCO}_2$ ), but a considerable reduction in  $\text{MC}_{\text{CCS}}$  can arise in the near future because of continuously technological improvements in CCS [8]. To give a breadth of findings, estimates of marginal cost avoided can be shared in three cost components: (1) marginal costs of carbon captured at the point of source, which range from US  $\$200/\text{tC}$  to  $\$250/\text{tC}$  [8]; (2) marginal costs of captured carbon transportation to storage, which range from US  $\$5/\text{tC}$  to  $\$10/\text{tC}$  per 100 km [8]<sup>5</sup>; and (3) marginal costs of carbon stored at the storage site, which range from US  $\$20/\text{tC}$  to  $\$55/\text{tC}$  [14].<sup>6</sup>

## 4. CCS benefits

### 4.1. Private benefits and public benefits from employed CCS technologies

The private benefits of carbon capture and storage include the proven ability of injecting  $\text{CO}_2$  underground into geologic crude oil and natural gas deposits to enhance extraction of oil and gas from these deposits. These benefits can be quantified by multiplying the price of the additional crude oil or natural gas extracted as a result of  $\text{CO}_2$  injection by the going market price of oil or gas. As this chapter is currently being written in early 2016, the real prices of crude oil and natural gas resources received by oil and gas producers are at record lows worldwide. These relatively low prices have a negative impact on the private benefits of  $\text{CO}_2$  injection projects for enhancing oil and gas projects.

Thus, a critical component of whether or not such projects will be economically feasible to oil and gas companies is the expected price path of future oil and gas prices. Such price paths are difficult to estimate empirically [2, 8, 11]. However, based on economic theory and Hotelling's rule in particular, we expect theoretically that the market price of any exhaustible, non-renewable natural resource, including crude oil and natural gas, to follow an upward-sloping price path in the long run as the resource becomes scarcer.

<sup>3</sup>For consistency, in the chapter the units of  $\text{MtC}$  and US  $\$/\text{tC}$  are being used to describe economic values for marginal costs and benefits on average, assuming  $\text{MC} \approx \text{AC}$  in all long-run CCS operations. We will note where the units of  $\text{MtCO}_2$  and US  $\$/\text{CO}_2$  are applied as alternative measures. All are equivalent: (1) US  $\$27.3/\text{tCO}_2$  (= US  $\$100/\text{tC}$ ) [26]; (2) US  $\$10/\text{tCO}_2$  is approximately equivalent to US  $\$37/\text{tC}$  [15].

<sup>4</sup>Because the atomic weights of carbon are 12 atomic mass units and carbon dioxide is 44 atomic mass units, a ratio factor of 3.67, or  $44/12$ , is used, meaning one ton of carbon equals 3.67 tons of carbon dioxide, which can also approximately equal  $1 \text{ tC} = 3.7 \text{ tCO}_2$  (as computed from  $(\text{US } \$37/\text{tC}) \div (\text{US } \$10/\text{tCO}_2)$ , or  $3.66 \text{ tCO}_2 = (\text{US } \$100/\text{tC}) \div (\text{US } \$27.3/\text{tCO}_2)$ ). However, only the factor of 3.67 is applied for computation of all estimates in this chapter.

<sup>5</sup>These costs can be easily and quickly observed in Anderson and Newell (2004) (please see Table 3 in Ref. [8]).

<sup>6</sup>The later measures may be slightly higher after having been adjusting for inflation over time. Assuming a gas price of US  $\$3$  per million Btu (MBtu), which was the average price over the past decade, transport and storage costs of  $\$37/\text{tC}$  stored were reported in [8]. Moreover, one can apply the following formulas to see how adjusted/expected benefits and costs are affected by inflation rates over time, that is, adjusted benefits in current-year = dollars in base-year  $\times (\text{CPI}_{\text{Current-year}} / \text{CPI}_{\text{Base-year}})$ , and adjusted costs in current-year = dollars in base-year  $\times (\text{PPI}_{\text{Current-year}} / \text{PPI}_{\text{Base-year}})$ , where CPI is the consumer price index, and PPI is the producer price index.

From economic theory, we can also predict that increasing market prices of exhaustible, non-renewable energy resources such as crude oil and natural gas will eventually lead to the substitution of these relatively high-cost energy sources by relatively cheaper energy sources. For example, sometime in the future it may be economically feasible and desirable to shift completely over to some “backstop technology” for producing energy including solar and wind power and the “holy grail” of virtually unlimited energy production—nuclear fusion ([5], Chapter 3).

In addition to the private benefits to oil and gas companies of CCS projects that enhance oil and gas production, private benefits of CCS projects as a whole also include private benefits of global warming mitigation such as reduced health costs to individuals, reduced damages to agricultural crops, and reduced damages to human-built structures in flood-prone areas. These private benefits can be quantified using private health-care expenditures, the market value of agricultural crops, and the costs of replacing or repairing human-built structures [16].

There are also many public benefits of CCS projects associated with global warming mitigation. These public benefits include economic values associated with protecting fish and wildlife habitat (e.g., Polar Bear habitat in Arctic regions) and human cultures (e.g., Indigenous, Native or First-Peoples in Arctic regions). Non-market economic valuation techniques including contingent valuation and choice experiments can be used to quantify these types of nonmarket benefits ([5], Chapter 13).

The total benefits of carbon capture and storage ( $T B_{ccs}$ ) can be expressed in the equation form as

$$T B_{ccs} = (T P B_{ccs}^s) + (T S B_{ccs}^s) \quad (3)$$

where,

$T P B_{ccs}^s$  is the total private benefits of carbon captured and stored

$T S B_{ccs}^s$  is the total social benefits of carbon captured and stored.

For economic efficiency purposes, we must also measure the marginal benefits of human-engineered CCS. The short-run marginal costs (MBCCS) of human-engineered CCS are defined as

$$M B_{ccs} = \frac{\partial T B_{ccs}}{\partial Q_{CO_2}} \quad (4)$$

where  $Q_{CO_2}$  is the quantity of CO<sub>2</sub> captured and stored.

## 4.2. Measures of total marginal benefits of CSS

In Section 4.1, we describe that the total benefits of carbon capture and storage technologies are received by both public and private entities. For economic efficiency analyses, we use the total marginal benefits of human-engineered CCS (MBccs) given by the private marginal



benefits of carbon captured and stored (PMBccs) plus the social marginal benefits (SMBs) of carbon captured and stored (SMBccs). In the following sections, we discuss quantitative estimates of the private marginal benefits of CCS (PMBccs) and the social marginal benefits of CCS (SMBccs).

#### 4.2.1. Private marginal benefits and carbon capture and utilization

A Canadian Pembina Institute Publication [17] reported post- $\text{CO}_2$  capture diverging into two pathways—carbon sequestrations (CCS) (already discussed so far) and carbon capture and utilization (CCU) (discuss in this subsection). CCU applications fall under two main approaches: the conversion approach and nonconversion approach.<sup>7</sup> Since the twenty-first century, technological advances have made various CCU applications under these two main approaches more practical and profitable [18–20].

CCU conversion approach applications range from mineralization (e.g. varied utilized forms of carbonate applications), biological transformation (e.g. algae cultivation applications), and chemical transformation (e.g. liquid fuel applications including methanol, polymer/chemical feedstock, and urea yield boosting<sup>8</sup>). CCU non-conversion approach applications are generally aimed for the purposes of desalination and enhanced techniques including enhanced oil recovery (EOR), enhanced geothermal systems, and enhanced coal-bed methane [17].

Thus, the economics of CCU technologies then lies in potential net benefits received from reutilizations of the captured  $\text{CO}_2$ . Within 5–10 years, CCU conversion approaches including mineralization (considered as permanent-based performance) and biological and chemical innovations (considered as non-permanent-based performance) have been estimated to be utilized in a range of 5 to more than 300  $\text{MtCO}_2$  per year [17]. Within the same time frame, CCU nonconversion approaches will yield, in both permanent and non-permanent potential performance, an estimated 5–300  $\text{MtCO}_2$  in enhanced techniques and between 30 and 300  $\text{MtCO}_2$  in desalination [17].<sup>9</sup>

According to Refs. [21, 22], it is estimated that each year about 80%, or 9 million metric tons (MtC) of captured  $\text{CO}_2$  used by commercial industry, are in EOR operations. The net marginal benefits (PMBccs) of stored carbon to EOR and enhanced coal-bed methane recovery operations have been estimated in the range of US \$15/tC to \$30/tC [23].<sup>10</sup> There certainly exist

<sup>7</sup>CCU is also called carbon capture and reuse or carbon capture and recycling (CCR) [17].

<sup>8</sup>Urea, also known as carbamide, is an organic compound with the chemical formula  $\text{CO}(\text{NH}_2)_2$  and one of the most common forms of solid nitrogen fertilizer. Urea is produced by the reaction between ammonia and  $\text{CO}_2$ . See ([24], Appendix B).

<sup>9</sup>Permanent and non-permanent potential performances are referred to permanent and non-permanent storage. According to the Global CCS institute, reuse technologies that permanently store  $\text{CO}_2$  are considered to be an alternative form of CCS and referred to as “alternative CCS.” EOR, ECBM, EGS, carbonate mineralization, concrete curing, bauxite residue carbonation, and potentially algae cultivation (depending on the end product) are considered to be alternative forms of CCS. See ([24] Part I: Section 3.2).

<sup>10</sup>In recent work [25], it was estimated that EOR storage of  $\text{CO}_2$  could generate net benefits as high as \$335/tC stored, or cost as much as \$270/tC stored. In a base-case calculation, EOR generates average net benefits of about \$45/tC stored [8].

additional net benefits from other applications described above, but empirical estimates of these benefits are not yet available.

#### 4.2.2. Social marginal benefits

Unlike quantifying direct total private benefits, an attempt to measure public or social benefits can be quite a challenging task for researchers since there involve concepts of types of costs and nonmarket valuations of public goods and services provided to the population.

Before it is attempted to explain how social marginal benefits arrive in this subsection of the chapter, there are three concepts needed to explain since we simply use the reported range (not derived explicitly) of the estimates for SMB from various sources. First of all, we simply define that private costs are the costs that individual decision makers are facing given actual established market prices. Second, social costs are the private costs plus the costs of economic externalities on society. These social costs are the prices derived from market prices, where opportunity costs are taken into account. Finally, social cost of carbon (SCC) is the discounted monetized sum of the annual net losses from impacts caused by an additional unit of carbon emitted presently and is measured in US \$/tC or US \$/tCO<sub>2</sub> ([26] Chapter 3, p. 135).

According to the economic theory, at an economically efficient mitigation level the marginal social benefits of carbon reduction (SMB) are equal to the social costs of carbon, where SCC is defined as avoided total damages for an additional ton of carbon abated ([26], Chapter 3, p. 233). Thus, using estimates of SCC ([26], Chapter 20) and the assumption that  $SCC = SMB$  at an economically efficient carbon price, we can infer estimates of  $SMB_{CCS}$  currently in the range US \$14/tC to \$350/tC (or US \$4/tCO<sub>2</sub> to \$95/tCO<sub>2</sub>).<sup>11</sup> By assuming a 2.4% per year increase in emissions, the estimated range for  $SMB_{CCS}$  in the year 2030 is between US \$29/tC and \$694/tC (or US \$8/tCO<sub>2</sub> to 189/tCO<sub>2</sub>).<sup>12</sup> By adding private marginal benefits ( $PMB_{CCS}$ ) from the previous section to social marginal benefits ( $SMB_{CCS}$ ) from the current section, we estimate total marginal benefits of CCS ( $MB_{CCS}$ ) to fall in a range of US \$29/tC–\$380/tC currently to US \$49/tC–\$735/tC in 2030.<sup>13</sup>

## 5. Optimal CCS provision

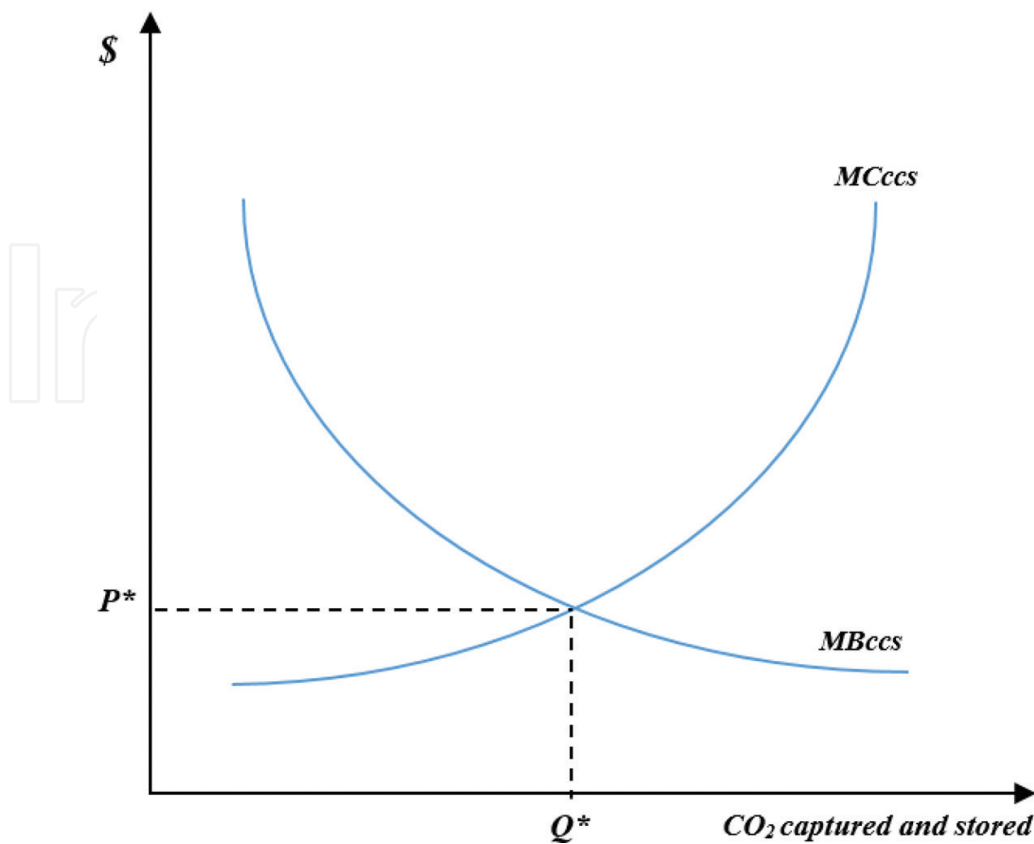
### 5.1. Concept of economically efficient level of CSS size

According to economic efficiency, the optimal level of carbon capture and storage is where the marginal benefits and marginal costs of CO<sub>2</sub> captured and stored are equal. In **Figure 1**, we show the marginal benefit curve for CCS ( $MB_{CCS}$ ), and the marginal cost curve for CCS ( $MC_{CCS}$ ). The marginal benefit curve is downward sloping because, following the law of diminishing

<sup>11</sup>Median and 95th percentile estimates reported in [27].

<sup>12</sup>The estimated social cost of carbon reported by [28] including uncertainty, equity weighting, and risk aversion is \$44 per ton of carbon (or \$12 per ton CO<sub>2</sub>) in 2005 US\$. Second, including uncertainty increases the expected value of the SCC by approximately 8%. Finally, equity weighting generally tends to reduce the SCC.

<sup>13</sup>For consistency, we assume there is also a 2.4% per year increase in the  $PMB_{CCS}$  reported in [23]. Thus, for 2030 the estimated range for  $PMB_{CCS}$  is between US \$20/tC and \$41/tC.



**Figure 1.** Economically efficient level of CCS.

returns, each additional unit of CO<sub>2</sub> captured and stored provides less private and social benefits. The marginal cost curve is upward sloping because both the private and social costs of CCS go up with each additional unit of CO<sub>2</sub> captured and stored. The upward-sloping nature of the marginal cost curve indicates that it would be very expensive (and likely cost prohibitive) to capture and store 100% of all CO<sub>2</sub> found in emissions from a point source such as a coal-fired power plant or industrial factory.

The economically efficient level of CCS ( $Q^*$ ) is shown graphically in **Figure 1** where the marginal benefit curve and marginal cost curve for CCS cross; at this point,

$$MC_{CCS} = \frac{\partial TC_{CCS}}{\partial Q_{CO_2}} = MB_{CCS} = \frac{\partial TB_{CCS}}{\partial Q_{CO_2}} \quad (5)$$

If all private and social benefits and costs of CCS could be “internalized” into economic markets, transactions between buyers and sellers could lead automatically to an economically efficient level of CCS, given certain conditions (e.g., perfect competition). It is notoriously difficult, however, to “internalize” all social benefits and costs because of the public good (or “bad”) characteristics of these benefits and costs such as nonexclusiveness and nonrivalry. Thus, achieving an economically efficient level of CCS would most likely require some degree of government intervention into markets such as economic incentives (e.g., taxes and subsidies) and/or direct regulation ([5], Chapter 10).

## 5.2. Estimates of CSS optimal level

As previously described in this chapter, under the condition where marginal benefits and marginal costs of CO<sub>2</sub> captured and stored are equal, there exists a relationship between the optimal carbon price and the optimal level of carbon capture and storage. For a given carbon price range of US \$146–\$257/tC (or US \$40–\$70/tCO<sub>2</sub>), the optimal level of CO<sub>2</sub> captured and stored is in the estimated range of 0–8MtC (or 0–29.48MtCO<sub>2</sub>) per year [29, 30].

## 6. Summary and conclusions

From a public policy perspective, since the general public also benefits from carbon dioxide being captured, stored, and prevented from entering the atmosphere, there is economic justification for public policies targeted at providing economic incentives for private companies to invest in CCS technology, such as direct subsidies or tax breaks. Whether or not CCS technology will prove to be one of the “tools” in the global warming, mitigation “tool box” in the long run is yet to be seen.

In addition to the Petra Nova project in the United States, private companies in Canada, Germany, and China are investing in large-scale CCS projects, with mixed economic feasibility results from a private firm perspective. Scaling-up from the private firm level to the society level where public benefits from global warming mitigation are taken into account, the private and public economic benefits of CCS projects seem likely to outweigh the private costs. Thus, public policies, which help private companies to defray the high costs of large-scale CCS projects, may be justified from an overall benefit-cost analysis perspective.

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